

Gas Displacement and Aggregate Stability of Soils¹

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ABSTRACT

When surface soils are dry, O_2 and N_2 are adsorbed on the external mineral surfaces. In the process of wetting the soil, water molecules displace the adsorbed O_2 and N_2 molecules to the gas phase where they can be measured, as was done in this study. These gases, released from the adsorbed phase, join entrapped air in the gaseous phase as the primary factor disintegrating aggregates when soils are wet quickly. Adsorption of N_2 and O_2 occurs on surface soils during hot dry afternoons as the water molecules leave the surface. During cool nights, relative humidities commonly rise above 50%, allowing more strongly adsorbed H_2O molecules to displace adsorbed O_2 and N_2 . Release of this adsorbed N_2 and O_2 causes aggregates wetted by immersion during hot afternoons to be less stable than aggregates of the same soil wetted in the morning.

Additional Index Words: air entrapment, adsorption of air, aggregate disintegration, molecular adsorption, relative humidity.

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WATER CONTENT prior to immersion is a major factor in the wet sieve stability of most soils (Panabokke and Quirk 1957; Kemper and Koch 1966). For many soils, most of the aggregate breakdown occurring during immersion is avoided if the soils are evacuated prior to immersion. This fact has led to the conclusion that entrapped air is a primary factor in the breakdown of these aggregates when immersed. Weakly adsorbed, nonpolar molecules such as O_2 and N_2 do not usually penetrate the interlayer surfaces of minerals. Polar molecules, such as water are strongly adsorbed and can penetrate to the interlayer surfaces (Mortland and Kemper 1965). This study was designed to determine whether appreciable amounts of air (primarily N_2 and O_2) are adsorbed on the surfaces of soil components, and whether release of this adsorbed air could be a factor in the aggregate stability of soils.

PROCEDURE

A sample of Portneuf soil (coarse silty mixed mesic, Durixerollic Calciorrhids) (19% clay, 63% silt, 18% sand with 0.7% organic matter) which had been air-dried, sieved through a 2-mm sieve, and stored for several years was used in this study.

One hundred grams of soil, dried over P_2O_5 or in an oven at 105°C were placed in a 125-mL erlenmeyer flask as indicated in Fig. 1. A vial containing the desired amount of water was placed in the upper part of the flask. A small hole in the bottom of the vial allowed the water to move into the soil over a period of about 1 hr. As soon as the vial was placed in the flask and capillary contact of the water with the soil established, the stopper was fitted into the mouth of the flask, connecting the flask to the manometer indicated

in Fig. 1. The tubing outlets were then closed sealing the system so subsequent increases in pressure were read by the manometer. This assembly was housed in a constant temperature room (24°C) and pressures in the flasks were monitored for 48 h following insertion of the water.

Diurnal changes in the water content of Portneuf soil were measured by placing 4-g samples of 1- to 2-mm aggregates on brass screens (24 wires 0.165 mm in diameter per cm) and placing these on the bare field soil surface. Water contents of the aggregates were determined gravimetrically at 1500 and at 0700 h. Water contents of the surface 5 mm of Adelanto soil were monitored as described by Jackson, (1973).

Aggregate stabilities of the Portneuf and Adelanto soils were determined by wet-sieving 4-g samples in an apparatus similar to that described by Kemper and Koch (1966). Samples of each soil were placed on sieves, dried over P_2O_5 and weighed. Ten samples from each soil were placed in a humidifying chamber for increasing lengths of time until they had adsorbed from 0 to 30% water.

The samples were then equilibrated in closed containers for a few hours, weighed to determine water contents, immersed in water, and oscillated up and down as described by Kemper and Koch (1966) for 3 min. Aggregates > 0.25 mm remaining on the screen following this treatment were considered stable.

RESULTS AND DISCUSSION

Molecules of O_2 and N_2 adsorbed on the dry soil surfaces were displaced into the gaseous phase by the H_2O as indicated by the pressures which developed in the flasks (Fig. 2). Initial increases in pressure were probably due to both the displaced $O_2 + N_2$ and to temperature increases in the flasks due to a substantial heat of wetting (Anderson, et al. 1963). However, this heat was dissipated via conduction within a few hours.

Steady pressures (after 24 h.) are plotted as a function of the amount of water added to the sample in Fig. 3. These pressures indicate little additional displacement of $N_2 + O_2$ when water was added in excess of that required to form a monolayer of water on the total surface area of the soil. This soil has a hydratable area of about 96 000 m²/kg as estimated from ethylene glycol monomethyl ether adsorption by the procedure outlined by Carter (1965). This pressure increase in about 95 cm³ of volume can be accounted for by about 0.00034 molecular weights of $O_2 + N_2$. Air, primarily O_2 and N_2 , has a weighted average molecular weight of about 29. Thus, it appears that about

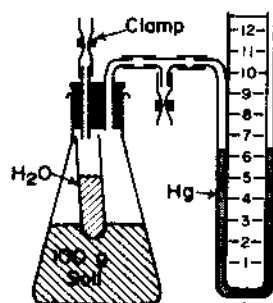


Fig. 1—Apparatus used to measure $O_2 + N_2$ released from soil by H_2O adsorption.

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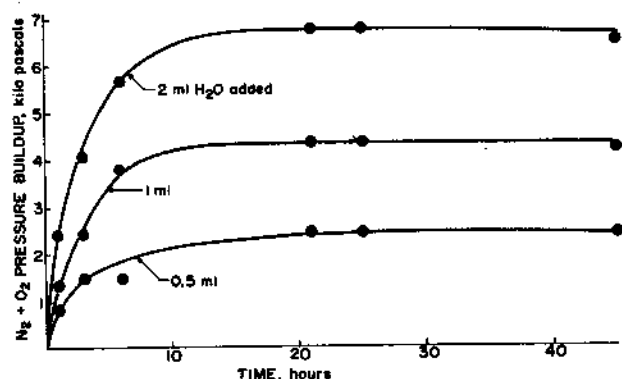


Fig. 2—Pressure change with time after adding H_2O to 100-g samples of dry Portneuf.

0.010 g of air was released, about 20% of the normal pore space of this soil when dry. Consequently, while the air adsorbed in dry soil aggregates and released by wetting is not the major component of air entrapped by rapid wetting, it is a significant addition.

The general effect of entrapped air on the aggregate stability of soils is indicated in Fig. 4. When the soil aggregates are wet under vacuum or wet slowly under tension so the air phase is not entrapped, their stability is greater than when they are quickly immersed in water.

The following calculation is an example of the disintegrating forces that adsorbed $O_2 + N_2$ may develop as they are displaced into the gas phase. Assume that the "external surface" in these aggregates is $10\,000\text{ m}^2/\text{kg}$ and that the adsorbed air ($0.0001\text{ kg } (O_2 + N_2)$ per kg soil) is adsorbed primarily on this external surface. Then the amount of $O_2 + N_2$ adsorbed per cm^2 of this "external surface" would be 10^{-8} or about $(10^{-9}/29)$. If two facing surfaces of a flat pore in this soil are 10^{-6} cm apart, the volume between two 1 cm^2 flat surfaces will be 10^{-6} cm^3 . Water will displace the adsorbed N_2 and O_2 from these surfaces. If liquid phase water is blocking the exit of this gas from this 10^{-6} cm^3 volume, the density of the $O_2 + N_2$ released from two cm^2 of the surface and added to the gas phase will be $(2 \times 10^{-9}/29)/10^{-6} = 6.9 \times 10^{-5}\text{ moles/cm}^3$ or $22\,600 \times 6.9 \times 10^{-5} = 1.56\text{ moles/molar volume} =$ about 150 kPa pressure.

If the mineral surfaces constituting the walls of the pore are $0.5 \times 10^{-6}\text{ cm}$ apart, the force developed by this displaced gas would be about 300 kPa. If they were $2 \times 10^{-6}\text{ cm}$ apart, the force would be about 75 kPa. In general, these forces are larger than the diffuse layer swelling forces developed when the volume between the opposing surfaces is filled with water. These forces originating from O_2 and N_2 displacement from the mineral surfaces are sufficiently large enough to break soil aggregates apart along planes which consti-

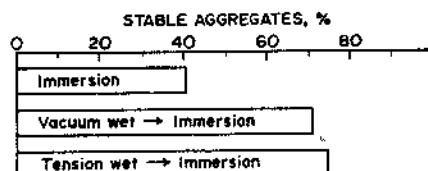


Fig. 4—Effect of wetting method on aggregate stability [average of 16 Western United States soils as measured by Kemper and Koch (1966)].

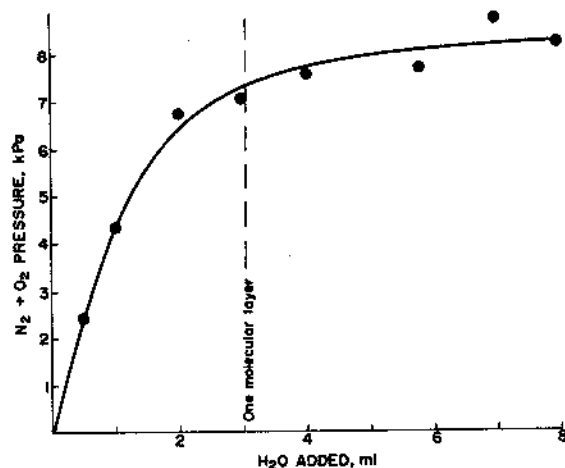


Fig. 3—Effect of water added on pressure buildup due to $N_2 + O_2$ displaced.

tute their external surface area. Microscopic observation of Portneuf aggregates during rapid wetting and subsequent disintegration into microaggregates showed no cloudiness between microaggregates. This indicates no appreciable dispersion of clay from the aggregates and that swelling induced by sorption of water into the diffuse layer of cations is not playing a major role in the breakdown of these aggregates. Consequently, it appears that the gas displacement forces primarily cause disintegration when this soil is wetted quickly. However, the relative roles of air displaced from adsorption sites on mineral surfaces and the entrapped and compressed gas phase air that was already in the pores is difficult to evaluate from this type of calculation.

Aggregate stabilities of the samples of Portneuf and Adelanto soils are shown in Fig. 5 as a function of their initial water contents (dry weight basis). Since the bulk densities of these aggregates are between 1.4 and 1.5 Mg/m^3 , the air-filled space within them constitutes about 45% of their volume and they become saturated when 1 g of aggregate contains about 0.3 g of water.

Apparently, air contained within the pores at water contents $> 18\%$ has little effect on aggregate breakdown of these soils. It is possible that a major portion of this air escapes before the particle is surrounded by water, since air is in the largest soil pores and is therefore relatively mobile. The capillary pressure exerted by the water on the air in these large pores is also much smaller, consequently pressures large enough to disrupt the aggregate apparently do not develop.

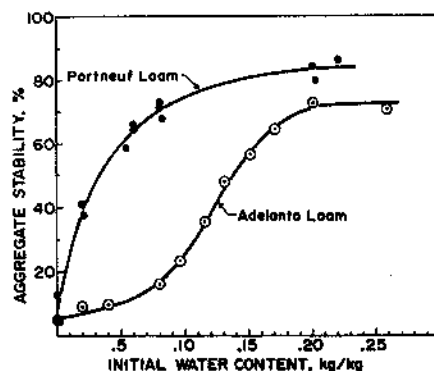


Fig. 5—Aggregate stabilities as a function of initial water content.

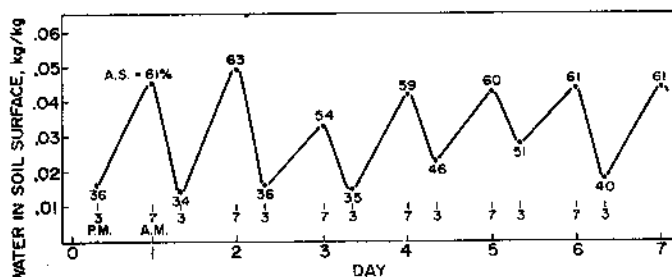


Fig. 6—Diurnal changes in water contents of aggregates on the surface of Portneuf soil during August 1982. Numbers associated with data points indicate percent aggregate stability expected based on Fig. 5.

Air entrapped within pores in the Adelanto aggregates when the initial water content was between 5 and 18% played a major role in the disruption of soil aggregates when wetted. Since about 3% water is sufficient to cover the mineral surface of this soil with a layer of water molecules, there would be practically no air ($O_2 + N_2$) adsorbed on those surfaces when initial water contents are $> 3\%$. This indicates that the entrapped and compressed gas phase creates sufficient force to disintegrate these aggregates and that air displaced from adsorption sites on the solid phase is not required to essentially complete this breakdown.

The Portneuf aggregates which had been stored for several years were much more cohesive than Adelanto aggregates. When the equivalent of one molecular layer of water was initially in these aggregates (i.e., 3%) and essentially no air was adsorbed, the aggregates were about 50% stable. However, when these aggregates were dry initially and the amounts of air discussed in the previous section were liberated during immersion, an average of $< 10\%$ of the aggregates remained intact. This indicates that the adsorbed air created pressures, during its displacement into the gas phase by adsorbed water, that caused considerably more aggregate breakdown than the capillary induced pressures resulting from the compression of air which was initially in the gas phase. Kemper and Rosenau (1984) indicate that the stability of Portneuf soil which has been recently cultivated is similar to that shown for the Adelanto, indicating major increases in cohesion of the Portneuf as a result of prolonged storage.

Water contents of aggregates on the surface of the Portneuf soil at 1500 h were generally equivalent to < 1 molecular layer of water on all surfaces (Fig. 6). During the nights they adsorbed water and by morning commonly had more than the equivalent of a molecular layer of water on all surfaces. Using the curve relating stability to initial water content for these Portneuf aggregates (Fig. 5), the aggregate stabilities at these water contents were estimated as shown in Fig. 6. In two cases aggregate stabilities were measured and were within 5% of the estimates.

Jackson (1973) monitored water contents continuously following an irrigation and the data shown in Fig. 7 are for the top 5 mm of the Adelanto loam. The stability vs. initial water content relation shown for the Adelanto soil (Fig. 5) was used to estimate aggregate stabilities shown numerically at the peaks and valleys of the curve in Fig. 7. The lowest water content for this soil is not as low as indicated for the Portneuf in Fig. 6 because the 5 mm-deep layer encompasses soil with higher moisture in its lower regions.

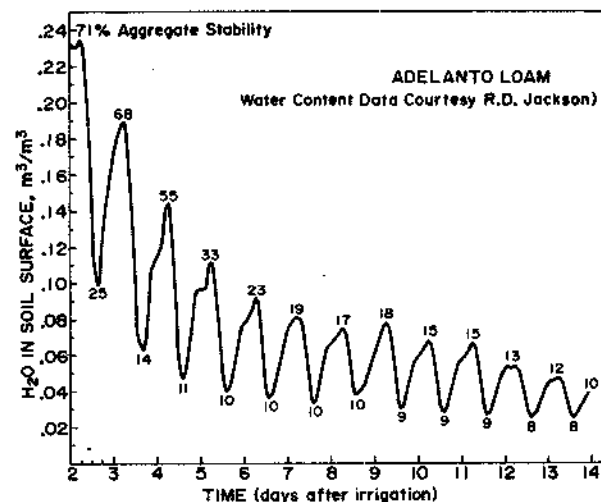


Fig. 7—Water contents in the top 5 mm of Adelanto soil following an irrigation (Jackson, 1973). Numbers associated with peaks and valleys represent aggregate stability expected based on Fig. 5.

In both cases a significant diurnal fluctuation of aggregate stability is expected.

Field attempts to measure the effect of diurnal changes in aggregate stability on intake rates of soils have not shown significant effects (Goel et al., 1982). However, this may have been due to the fact that when soil aggregates were dry and disintegrated more completely, water in the furrows was also warmer and its viscosity was lower. If the assumption that these two factors are balancing each other is applied to the data of Goel et al. (1982), a 26% decrease in intrinsic permeability of the soil during the hot afternoon would be needed to offset the decrease in the viscosity of the water.

CONCLUSION

In general, the data indicate that air (largely $O_2 + N_2$) is adsorbed on the Portneuf soil in significant quantities when the external surfaces of the soil minerals are not covered with water. When $O_2 + N_2$ adsorbed on dry mineral surfaces in soils are displaced by water and are confined to pores $< 10^{-6}$ cm wide, pressures in excess of 100 kPa can develop. These pressures can play a major role in the disintegration of aggregates.

Diurnal changes in H_2O vs N_2 and O_2 adsorbed in aggregates at soil surfaces are sufficiently large to cause large changes in aggregate stabilities.

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